Coastal ocean modelling with SLIM: application to the Columbia River ROFI

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www.climate.be/SLIM

The need for accurate coastal modelling

Unstructured grid models allow highly flexible spatial discretization and therefore accurate representation of complex phenomena, such as the hydrodynamics in Regions Of Freshwater Influence (ROFI) of large rivers, characterized by large density variations, rapid flow dynamics and complex topography. The whole river-sea continuum can therefore be simulated seamlessly.

The complex interactions between tides, river inflow and ocean dense waters in shallow areas lead to strong density gradients and rapid currents, often difficult to handle in a numerical model. Many models tend to stabilize the computations by adding diffusion, leading to overly-smoothed fronts.

In this poster, the aim is to analyze the baroclinicity of the SLIM model. The ability of stabilizing the density field is assessed through two different test-cases.

We first analyze the performance of the SLIM model on the lock-exchange test-case. As coastal waters feature strong density gradients, the baroclinicity needs stabilization. Therefore, we study the use of a Smagorinsky viscosity and different limiters.

We then analyze the plume of the Columbia River as simulated with SLIM in two different regimes of the Columbia River ROFI. The horizontal structure is discussed and compared to SELFE.

SLIM 3D

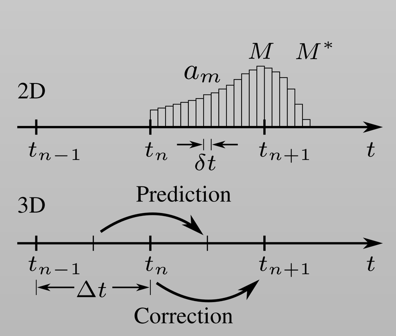
3D hydrostatic, Boussinesq equations :

$$\begin{cases} \frac{\partial \boldsymbol{u}}{\partial t} + \nabla_h \cdot (\boldsymbol{u}\boldsymbol{u}) + \frac{\partial (w\boldsymbol{u})}{\partial z} + f\boldsymbol{e}_z \wedge \boldsymbol{u} + g\nabla_h \eta + g\nabla_h r \\ \qquad = \nabla_h \cdot (\nu_h \nabla_h \boldsymbol{u}) + \frac{\partial}{\partial z}\left(\nu \frac{\partial \boldsymbol{u}}{\partial z}\right) \\ \frac{\partial \eta}{\partial t} + \nabla_h \cdot \int_{-h}^{\eta} \boldsymbol{u} dz = 0 \\ \frac{\partial w}{\partial z} + \nabla_h \cdot \boldsymbol{u} = 0 \\ \frac{\partial T}{\partial t} + \nabla_h \cdot (\boldsymbol{u}T) + \frac{\partial (wT)}{\partial z} = \nabla_h \cdot (\mu_h \nabla_h T) + \frac{\partial}{\partial z}\left(\mu \frac{\partial T}{\partial z}\right) \\ \frac{\partial S}{\partial t} + \nabla_h \cdot (\boldsymbol{u}S) + \frac{\partial (wS)}{\partial z} = \nabla_h \cdot (\mu_h \nabla_h S) + \frac{\partial}{\partial z}\left(\mu \frac{\partial S}{\partial z}\right) \end{cases}$$

- $\boldsymbol{u}$: horizontal velocity
- w : vertical velocity
- η : water elevation
- T : temperature
- S : salinity
- $\rho = \rho_0 + \rho'(z,T,S)$: density
- ρ_0 : reference density
- $r = 1/\rho_0 \int_z^{\eta} \rho' d\zeta$: baroclinic head
- f : Coriolis factor
- $\boldsymbol{e}_z$: vertical unit vector
- ∇_h : horizontal gradient operator
- ν_h, ν : horizontal and vertical turbulent viscosity
- μ_h, μ : horizontal and vertical turbulent diffusivity

Finite Element discretization

- Piecewise Linear Discontinuous Galerkin prismatic elements
- Mode splitting time integration scheme
  - Third order Leap-Frog-Adams-Moulton predictor-corrector (from ROMS)
  - Explicit, only vertical diffusion is treated implicitly
  - For each time step, 2D equations are advanced by M^* sub-iterations using a third order Adams-Bashforth scheme
- Moving mesh accounting for the free surface with an ALE formulation
- Slope limiter for tracers and velocity
- Coupled with GOTM turbulence model



Representation of the time marching [3]

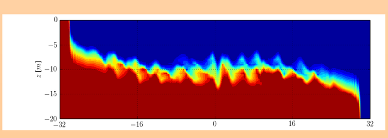
The lock-exchange test-case

The ability of the SLIM model to capture the density-driven currents is assessed with the lock-exchange test-case (also called dam break test-case). A long shallow domain is initially filled with two fluids of slightly different densities. The barrier separating those two fluids is then removed and the exchange flow drives the denser fluid under the lighter fluid.

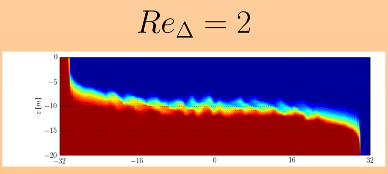
In order to stabilize the baroclinicity, the viscosity is parametrized with a Smagorinsky formulation : $\nu = (C_s\Delta)^2|S|$, where C_s is a dimensionless parameter, Δ is the grid size and S is the deformation rate [1].

The mesh Reynolds number (Re_Δ) associated with this Smagorinsky formulation can be approximated by $C_s = \frac{1}{\sqrt{Re_\Delta}}$. Based on numerical considerations, Re_Δ should be around 2 [1,2], but this value can depend on the advection scheme used.

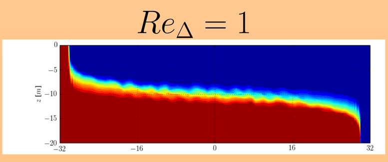
This viscosity does not ensure the monotonicity of the tracers. In that purpose, we investigate the effects of two kind of limiters. A jump-based diffusivity is first defined as $\kappa = \kappa_0 f([[T]])$, where κ_0 is a standard diffusivity calculated with the local velocity and mesh size, and $f([[T]])$ is a monotonic function of the jumps in tracer field. On the other hand, a slope limiter corrects nodal values by the mean over neighbouring elements, preserving the mass inside each prism.



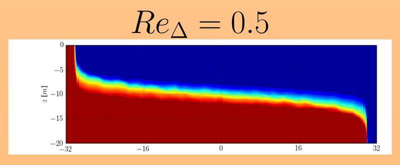
$Re_\Delta = 2$



$Re_\Delta = 1$

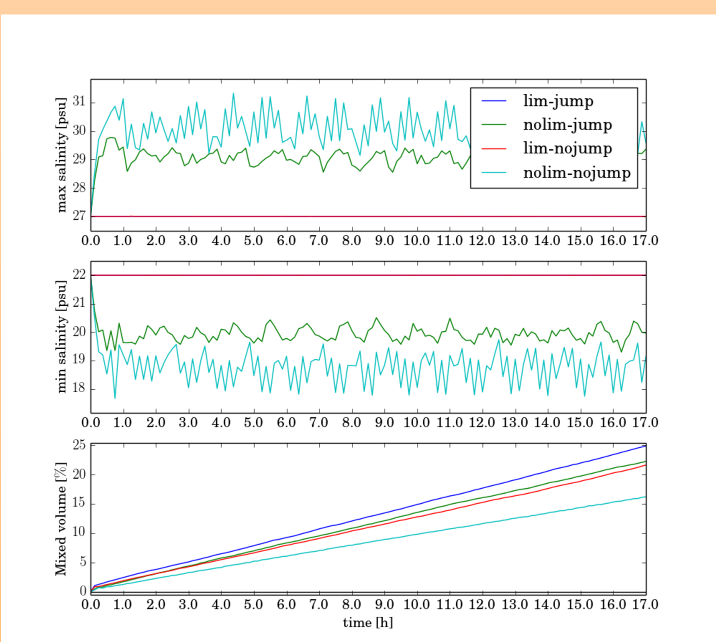


$Re_\Delta = 0.5$

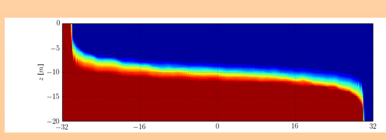


$Re_\Delta = 0.25$

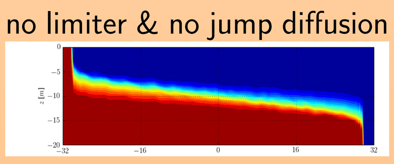
No limiter, $\kappa = 1\ \mathrm{m^2/s}$



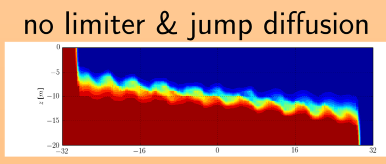
Time series of mixed volume and max/min overshoots



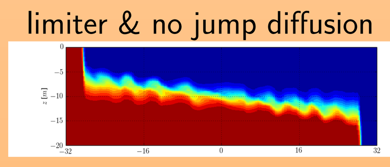
no limiter & no jump diffusion



no limiter & jump diffusion



limiter & no jump diffusion



limiter & jump diffusion

$Re_\Delta = 0.25$

- Small Re_Δ produce spurious oscillations
- These oscillations vanish as soon as $Re_\Delta < 0.5$
- The viscosity is therefore larger but the front remains sharp and the propagation speed does not decrease
- Overshoots are significantly smaller with the use of limiters
- Limiters generate spurious oscillations in the tracer field
- Limiters generate a comparable amount of mixing as a jump-based diffusivity
- As mixing occurs the propagation front is slowed down

What's next?

- Study and solve the oscillations produced by the limiters
- A fair comparison between SELFE and SLIM on the Columbia River plume to analyze the capabilities of both models

This work was funded by the Grant FSR (Fonds Spécial de Recherche).

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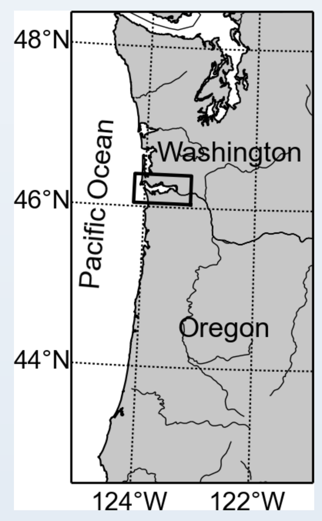
The Columbia River



With a river discharge ranging from $3,200$ to $10,500$ m^3/s, the Columbia River is the major freshwater source on the U.S. west coast, entering the Pacific Ocean.

Two main regimes of the plume have been identified:

- In the absence of wind, the plume is oriented northward due to the Coriolis force in the Northern hemisphere, and propagates along the coast up to Canada. A wind blowing from the south enhances this feature of the plume and the along-coast freshwater spread becomes thinner.
- On the other hand, strong wind from the North (late spring - early summer) drives the plume further offshore in a south-west direction. In this regime, the plume is detached from the coast.

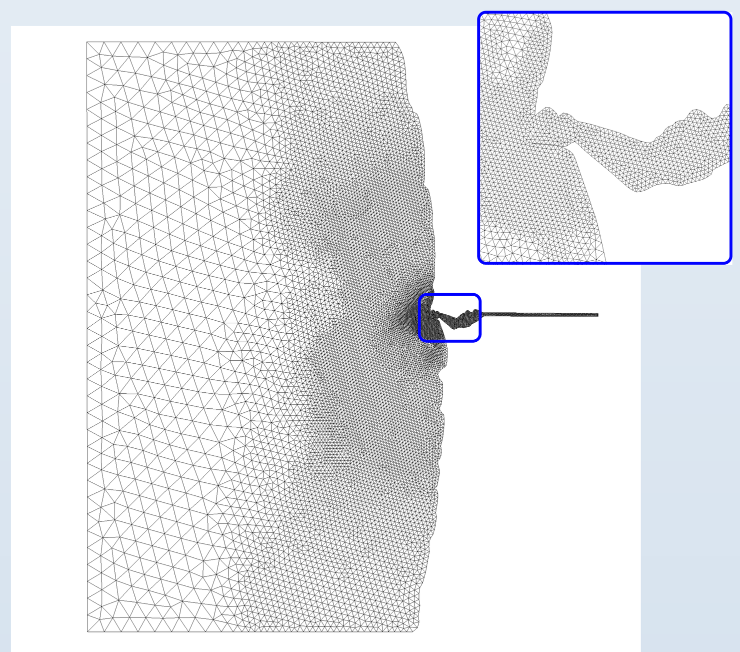
In this preliminary work, we try to simulate the above-mentioned regimes with SLIM.

Horizontal grid

The horizontal mesh is generated by GMSH (http://geuz.org/gmsh/). There are $21,000$ triangles with a length ranging from 500 m to 10 km.

The horizontal mesh is then extruded on the vertical to form $252,000$ prisms. The vertical grid used here is made of 12 σ-like coordinates, with increasing limited thickness (the grid turns into a z-levels grid in deep ocean).

The river part has been replaced by a long shallow channel as the focus is on the plume dynamics. The coastlines of the estuary are simplified to remove shallow bays and the minimal bathymetry is imposed at 4 m as there is no wetting and drying in SLIM3D.

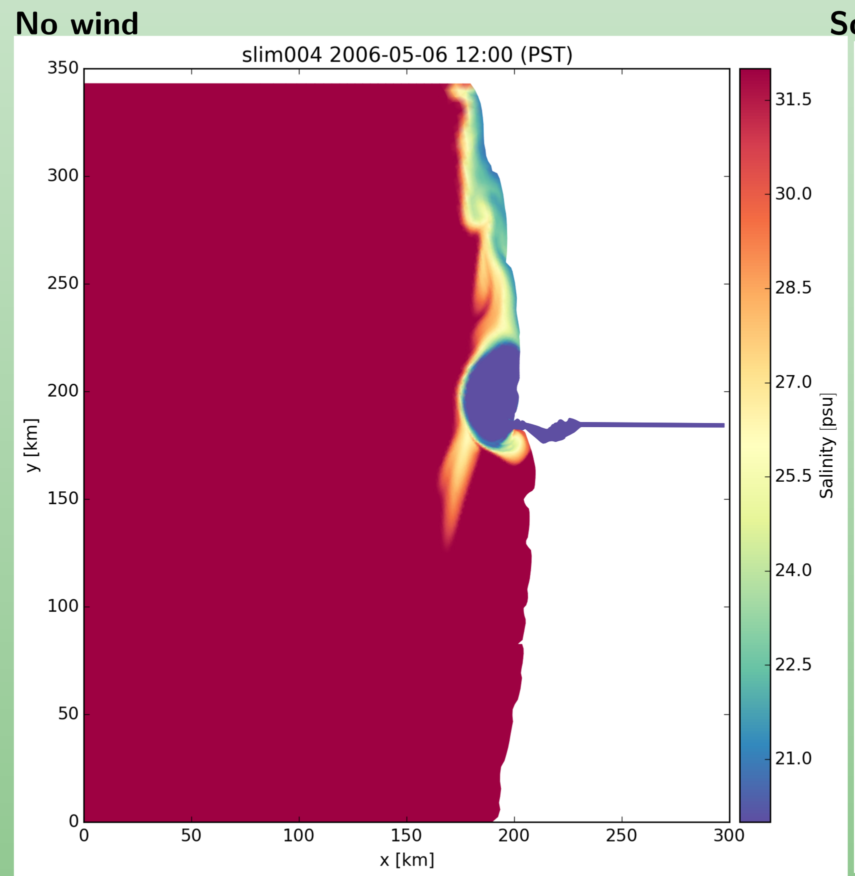


Set up

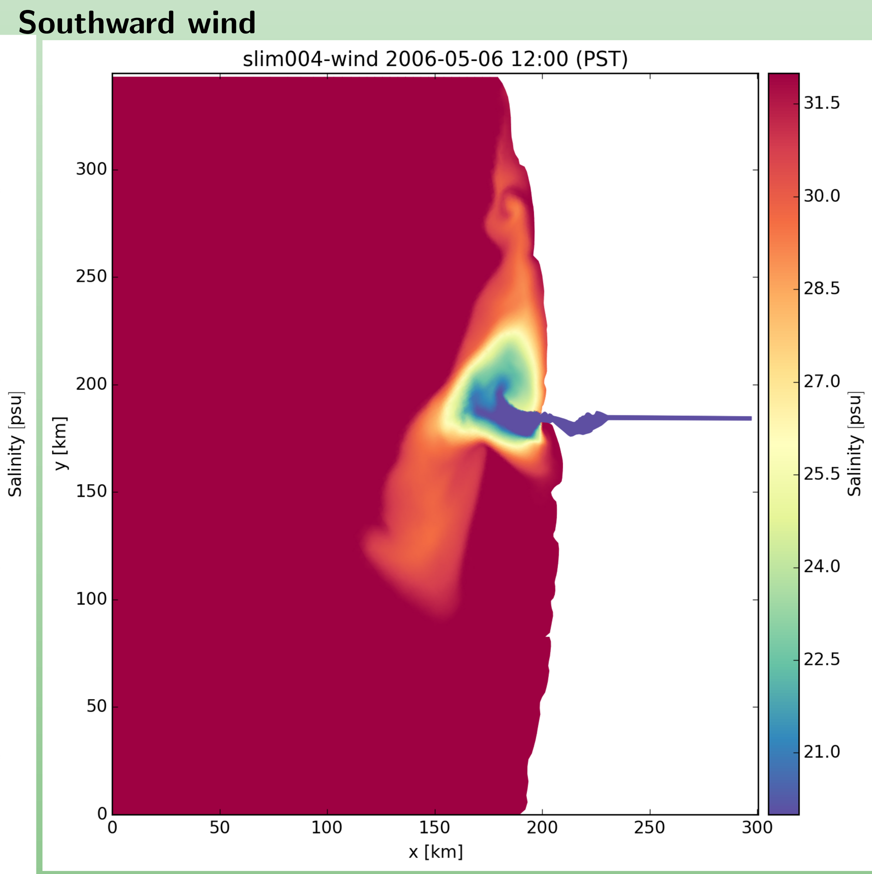
- Initial condition
  - Zero elevation and velocity
  - Stratified temperature in the ocean (from 6 to 14°C) and constant in the river (15°C)
  - Constant salinity in both the ocean (32 psu) and the river (0 psu)
- Open ocean boundary conditions
  - Elevations from SELFE previous run database
  - Weakly imposed stratified temperature
- Upstream
  - River discharge from measurements at Bonneville dam
  - Constant temperature ($15°C$) and salinity (0 psu)
- The bathymetry comes from SELFE database and is smoothed out in the ocean
- The 2D time step is calculated on the CFL condition for advection and is 0.5 s
- The 3D time step is 7.5 s ($M = 15$)
- The mesh Reynolds number is set to 0.25 (*see lock-exchange panel*)
- A jump diffusion is applied to the temperature and the salinity fields
- No other limiter is applied to the solution

Results

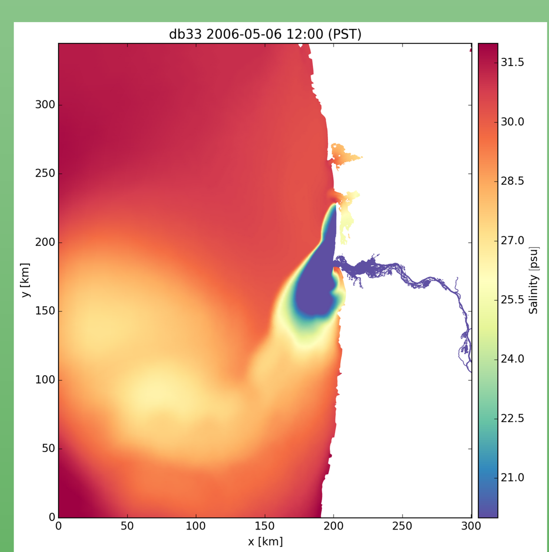
No wind



Southward wind



- As expected, the plume is oriented northward in the absence of wind
- A constant wind of 5 m/s changes dramatically the dynamics of the plume
- The simulations show rich fine structure in the plume even though the mesh is quite coarse



On the left panel is the same period as simulated by SELFE in the DB33 hindcast database. This long term simulation has been calibrated against data and used in many applications on the Columbia River.

Although the plume is quite different, due to the simplified forcings of the SLIM simulations, the SELFE simulation shows less fine structure.

These results suggests the discontinuous Galerkin formulation of SLM is less diffusive than the formulation of SELFE and may hence lead to an increased accuracy of the simulated coastal flow.

References

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